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Chief Engineer Goesta Salomonsson*: Underground Shale Oil Pyrolysis according to the Ljungstroem Method [Underjordisk skifferpyrolys enligt Ljungstroemsmetoden]

IVA, Vol. 24 (1953), No. 3, pages 118-123

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Code: 268-592?

UNDERGROUND SHALE OIL PYROLYSIS ACCORDING TO THE LJUNGSTROEM METHOD

The *in situ* principle for obtaining minerals, lying at various depths under the earth's surface, is not a new concept, at least not as it concerns a purely mechanical means of transportation up through the bore hole. It is sufficient, for example, to recall the use of steam for pumping up ground water or petroleum and to extract sulfur.

Markedly different is the modification involving a chemical reaction *in situ* followed by an extraction of the reaction products thus formed. The two methods which have achieved some technical significance are coal gasification and shale oil pyrolysis.

Coal gasification

Coal gasification, which has been studied for twenty years primarily in Russia, involves using thin or lean and therefore unworkable coal seams. Gas production occurs directly in the mine. The recoverable products should consist of carbon monoxide:

$$C + O_2 \longrightarrow CO_2$$
$$C + CO_2 \rightleftharpoons 2CO$$

The latter of the two reactions is, however, reversible, and at a lowered temperature displaces the balance toward the left. Since the exiting gas always passes a zone with a lower temperature before it leaves the seam, the balance is displaced towards the carbon monoxide and the thermal value of the gas decreases. In experiments performed with coal gasification

to a greater or lesser degree, gas with a very low thermal value was always obtained in accordance with this work, except where the coal seam contained bituminous substances, which by pyrolysis yields a gas containing hydrocarbons.

Shale pyrolysis

Oil shales are a sedimentary rock, which besides mineral components contain a varying amount of an organic substance named kerogen. By heating the kerogen to 400-600°C it is pyrolyzed, forming fluid and gaseous hydrocarbons with many volatile constituents. After pyrolysis there remains so-called shale coke consisting of the mineral components and a residue of kerogen (mainly coal).

Pyrolysis of shale *in situ* has been proposed by many in the world, but has been, as far as is known, carried out only according to Dr. Fredrik Ljungstroem's method at Svensk Skifferolje Aktiebolagets operations in Kvarntorp.

The shale is found there in one of the closest strata seams, 14-16 meters thick, overlain partly by limestone and earth, partly by just earth. Since it was found to be most expedient to place the Ljungstroem operation on the limestone covered shale, the covered shale was thus worked *in situ*, while the uncovered shale was mined and pyrolyzed in the furnaces.

The method involves placing an electric heating element down in vertical bore holes, going through the earth cover, the limestone cover and the shale seam, with the bore holes arranged in a hexagonal pattern (Figure 1). The bore hole is lined with a 2 1/4" iron pipe, to which the element, which consists of a corrugated band of a resistance alloy, is attached. The shale is horizontally laminated. During pyrolysis the pyrolysis gases flow into the crevices in the shale until they are discharged into the open bore hole in the center of the

hexagon. From this gas hole the gases are collected in a pipe network, which leads to condensation and bi-product plants. The pyrolysis causes a relatively large positive pressure in the mine, for which reason no fans are needed to transport the gas.

The electrical equipment encompasses a stationary transforming plant (132/22 kV), connected to the Royal Waterfall Authority network and to the Kvarntorp Works' Steam Power Center, a 22 kV transmission line, switching gear, 4 earth cables for 22 kV and 4 mobile 22,000/152 V field transformers. From the transformers energy was distributed via a network of cables and copper rails to the element in operation.

One of the elements dependent on input power is connected, and distributed over a zone running over the entire breadth of the field. 10,000 kW power corresponds to about 1,000 connected elements. Gradually as sufficient temperature in the mine is reached and pyrolysis is ready, a new element line is connected, whereby the entire part above the ground is moved forward a step. The element remains in the earth. A "warm front" moves thusly over the field (Figure 2).

After small-scale experiments the first Ljungstroem field with a field power of approximately 4 MW was established in 1942. At the end of 1945 when it was discontinued, it was handling about 14,400 m^2.

In April 1944 the first large-scale field was started, constituting a regular production entity within the Shale Oil Corp. This field had a combined input of about 20 MW, divided into two warm fronts of 10 MW each. The field was in uninterrupted operation until the fall of 1947, when the acute power shortage in the country forced the operation to shut down. A total of 415 million kWh was consumed and 64,000 m^3 of oil and 65 million m^3 of gas were produced, corresponding to a gain of 1 liter of oil + about 1 m^3 of gas per 6.4 kWh. 69,100 m^2 of field surface was used.

The results from the operation of that field showed that the new method was practical. With direction from the experience gained, the development and simplifying work was continued, with the aim of lowering the costs and electric energy consumption for the produced oil. The improvements so far advanced have been applied to the third Ljungstroem field, which, since power plants had been improved considerably, partly by the increase of the Kvarntorp Work's own steam power production, could be started in the spring of 1952, and which is now in operation with about 14 MW field input. Some of the most meaningful improvements are named here.

Reduced drill and material costs

In the Ljungstroem field II the drill pattern was that shown in Figure 1a, that is to say each hexagon had a gas hole. It appears, however, that the horizontal permeability to gas of the shale is sufficient to allow a longer flow path for the pyrolysis gas without the pressure falling too much. In field III therefore only every third hexagon has a gashole.

The distance between two adjacent element holes and the total energy input time are, of course, dependent on each other, since the input must continue, until each part of the shale mine reaches the pyrolysis temperature. In field II the hole distance was 2.20 m and the heating time about 150 days. Calculations have shown that the optimal working procedure should have greater hole distance. In field III the distance is therefore 2.64 m and the corresponding heating time 225 days (Figure 1b).

The savings in drilling, pipe, element and other costs with the new drill pattern is considerable, which are shown in the following comparisons:

Field II - per 100 m^2 of field area: 15.90 element holes + 7.95 gas holes = 23.85 holes

Field III - per 100 m^2 of field area: 11.04 element holes + 1.84 gas holes = 12.88 holes

i.e., the number of holes is reduced by 46%.

Reduced fringe costs

A certain part of the input energy in the field goes for making up for the losses in the form of heat loss to the hot shale masses' colder environment. The heat then flows up towards the earth's surface, down towards deeper lying strata and horizontally out toward the periphery. Even a part (a few percent) of the pyrolysis gases flows in the same direction because of the positive pressure in the mine. The losses in the vertical direction, taken as a percentage, of course, are not dependent on the size of the field, while the peripheral losses (in percent) are less the larger the field is, since the surface area of the field and therefore the total input energy increases as the square, while the field periphery increases linearly.

The following was obtained from the fields so far operated:

	area, m^2	periphery, m	$\frac{\text{periphery}}{\text{area}}$, m^{-1}	specific energy consumption kWh/ℓ oil
Field I	14,400	560	0.039	7.70
Field II	69,100	1,128	0.016	6.40

From the above it can be seen that an area of operation should preferably have a circular form in order to reduce the fringe costs to as low as possible, but this is not necessarily the most suitable in practical operation. One recognizes instead that the square form is the most economic, at least for quadrilateral

field formations. Attention must be paid, of course, to the size and depth of the shale layer, topographical character, existence of roads, water drainage, buildings etc., as well as optimal length of the connection cables and pipes between the mobile and the stationary apparatus.

Effective pumping away of ground water

The ground water in the mine must be pumped away as effectively as possible so that energy will not be unnecessarily used for water evaporation. Therefore, the level of the ground water stands higher in the surroundings than inside the field. Thus ground water flows into the field continuously, even if to some extent it is counteracted by the high gas pressure in the field. Keeping this inflowing ground water away is performed by a double row of pumps in front of and by the side of the warm fronts, lowered into the element hole, before the element is installed. The pumping is more effective the tighter the pumps are, that is to say the more concentrated the warm front is. The warm front accordingly should not extend over the entire breadth of the current operations area, without having to have a shorter, collected front, which relatively quickly moves itself over strip after strip of the field (something like ploughing a field). With the operation of the first field strip the losses are of course temporarily great, but the heat and the oil, which thereby seeps out along the strip's edge is stored in the shale lying closest outside and is useful in the operation of the adjacent field strip. This mode of operation is designed to be suitable for the present field III. The warm front occupies a surface there of 180 x 53 m^2

Use of secondary power

An important simplification measure which is taken is the use of secondary instead of primary power for a significant

part of the field's input. From the outset (the year 1944-1945) field II was fed with primary power (Figure 3a). The specific weight of the heat element and therewith the wall temperature in the element pipe was so high that it was considered too risky in regards to the life of the element to subject them to a varying load, e.g. through the use of secondary power. Through the improvement of the construction of the elements and the reduction of the specific weight towards the end of the heating period it was, however, possible to allow rapid short-term switching off without any damaging effects on the elements. Because of the partial shortage, which began in 1946, a mode of operation was attempted, which involved cutting off parts of the field during the peak load periods (Figure 3b).

The possibility of driving the field with varying charges is economically very advantageous, since the cheaper night and holiday rates can be used for a large part of the input. It has been shown to be appropriate, although not completely necessary, to have a lesser amount of constant power connected as a ground load. At the beginning of field III in the Spring of 1952 it was decided to apply this method of variable power supply. By running the Ljungstroem field and the Kvarntorp Work's steam plants together, it is now possible to hold a reduced power input during the daytime in the field, which is compensated for by a greater input of night power. Additionally a part of the power is cut off during peak hours in the daytime, so that not only does the withdrawal of water power cease, but also a certain input of steam power to the network can occur. The Ljungstroem field has in this way become to a greater extent than before an energy accumulator (Figure 3c).

Further progress toward this goal is possible by introducing seasonal power variations. The technique is thereby somewhat different than the connections and disconnections treated above.

The fact that shale does not give off oil at lower temperatures than about 280°C is utilized. A section of the shale field can be pre-heated accordingly to that temperature in the summer, when power is inexpensive, in order to effect pyrolysis with relatively little energy increase (i.e. heating to about 400°C) later in the wintertime. The "warm front" is divided in this way between a "pre-heating" and a "pyrolysis front." The pre-heating front can fluctuate over the fields at a certain distance from the pyrolysis front and the front's rate of fluctuation is determined by the power available in each specific case. The pyrolysis front fluctuates at a constant rate, which is set so that the average surface operated during the year is equally large for both fronts. Within the pyrolysis front variations over a 24-hour period can of course result. An even oil production is obtained in this manner in spite of a strongly varying power input. During an acute fuel shortage the pre-heated area can by pyrolyzed upon demand. The heat losses by the desulfurizing of the pre-heated area before pyrolysis is relatively insignificant in comparison with the better utilization of the secondary power. This mode of operation, which further accentuates the Ljungstroem field's energy accumulating character, has been used by the present field since the spring of 1953 (Figure 3d).

Current problems

Parallel to the above-mentioned major efforts in the development work, research continues concerning several problematic details of Ljungstroem methods, e.g. simplification of the drilling methods and element manufacture.

In cooperation with the Fuel Analysis of 1951 the possibility of combusting shale coke left in the earth for

use in pyrolysis of adjacent shale is being investigated. The idea is interesting, since thereby the field should be entirely independent of power supply.

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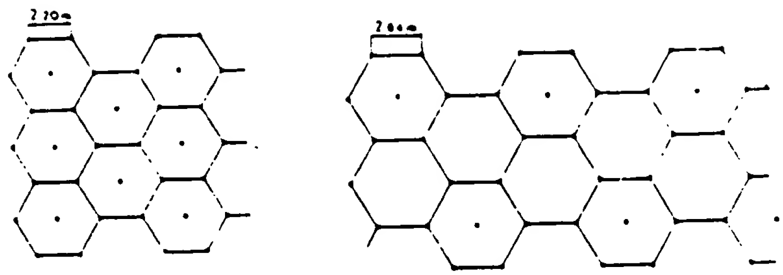


. element hole
· gas hole

a) Earlier hole pattern

b) Present hole pattern

Figure 1. Development of the pattern of drill holes.

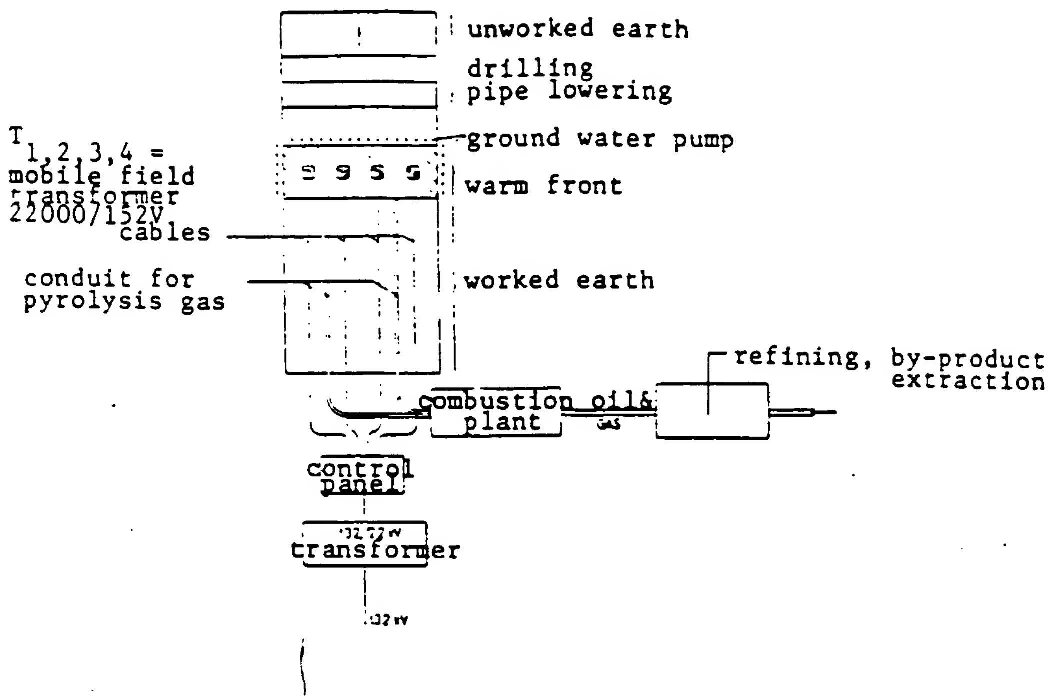
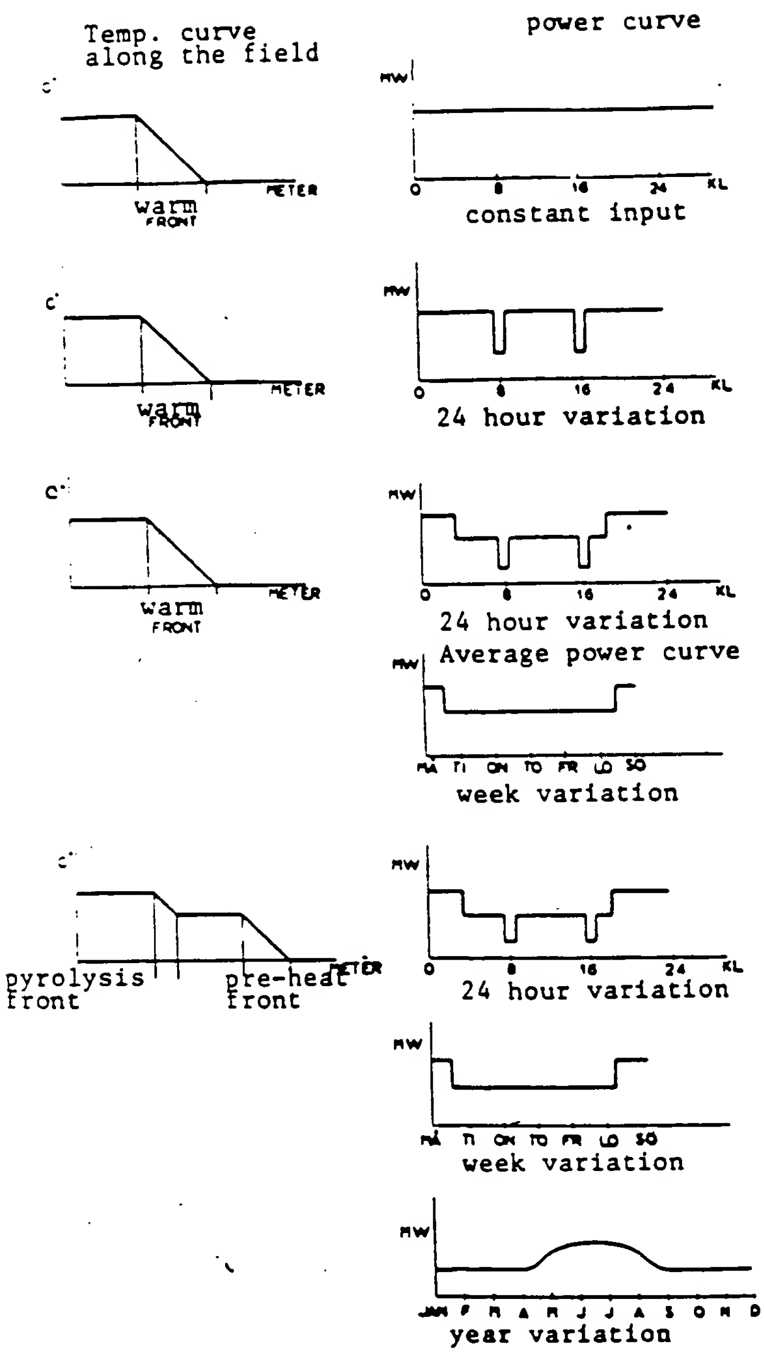


Figure 2. Diagram of a Ljungstrom field.



a. Constant power input.

b. Interruption of power supply during hours of top load.

c. Periodic power cut-offs and input of night and holiday power.

d. Periodic power cut-offs and input of night, holiday and summer power.

Figure 3.